Response to Reviewer's questions for: Dutta et al. Earth Surface Dynamics

We thank the reviewer for the thoughtful and thorough review of the manuscript. We are happy that apart from specific questions about the paper, he also raised general questions, which we think will go towards improving the manuscript. We have tried to answer all the queries put forth by the reviewer and we have also made corresponding improvements to the manuscript. Please find below the detailed response to the questions raised by the reviewer.

General Comments:

1) The results show that the sediment diffusivity differs considerably from the Rouse profile. It would be interesting to quantify the relevance of these results; i.e. what is the difference in sediment concentration profiles based on the Rouse profile and the improved profiles of the sediment diffusivity ?

Answer:

The authors appreciate the point put forward by the reviewer. In order to quantify the sediment diffusivity profiles, we have come up with a "mean shape factor" ϕ_1 for the profiles, calculated by vertically integrating the Kz profiles (see formula below). Using this non-dimensional number different vertical sediment diffusivity profiles can be differentiated among themselves and from the Rouse profile of Kz. In case that the ϕ_1 values for two different Kz profiles are the same (as two different distributions can have the same mean), we would then calculate "skew shape factor" ϕ_2 (see formula below). (D is the depth of the flow)

$$\phi_1 = \int_0^D \frac{K_Z(z)}{D} dz$$

$$\phi_2 = \frac{\int_0^D \frac{(K_Z - \phi_1)^3}{D} dz}{\left(\int_0^D \frac{(K_Z - \phi_1)^2}{D} dz \right)^{3/2}}$$

Next we will compare the actual sediment concentration profiles (from DNS and experiments) with sediment concentration profiles calculated based on the Rouse profile, this will help us quantify the relevance of the "improved" Kz profiles. For plotting experimental data the bottom concentration is normalized to one by dividing the whole profile by the "reference concentration" at the bottom (similar to Cellino and Graf 1999). The height from the bed where the reference concentration is measured is $y_{ref} = 0.05D$, where D is depth of the flow.

2) Is the following interpretation correct: because of the reduced turbulence activity with increasing self-stratification, more energy is available for the mean flow, which explains the increase in mean flow velocity? What is the physical process that causes the increase in turbulence activity in the upper part of the channel ?

Answer:

One of the effects of the self-stratification is reduction of the bottom drag; this can be seen in the total shear-stress plot provided below (Dutta 2012). The decrease in drag results in an increase in flow-discharge in the channel, as the force driving the flow is same as the non-stratified case. The reduction of the bottom drag is connected to the reduction of turbulence activity, which in turn reduces the Reynold's stress thus eventually reducing the total drag at the bottom. We have modified the manuscript to make the above point clearer. Near the top wall, turbulent activity is maintained due to lack of stratification in these regions. The small increase in turbulent activity is due to the increased flow discharge, which also increases other flow related parameters near the top wall (like total drag, see figure below).

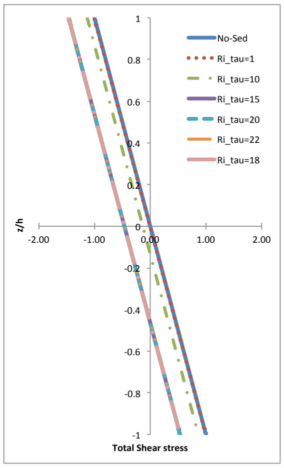

Figure 2.10: Mean non-dimensionalized total shear stress ($\tilde{\tau}_{tot}$) for increasing Ri_τ and $\tilde{V} = 0.025$. $\tilde{\tau}_{tot}$ profiles are linear and gradually shifts towards the channel bottom with increase in Ri_τ.

Figure 1

3) The effects of self-stratification seem to be much less important in the boundary layer flow (Figure 8) than in the channel flow (Figure 4). How can this be explained?

Answer:

The major difference between the boundary layer DNS and the channel flow DNS is the shear stress developed at the bottom. For the same shear Reynolds number (Re_τ) the shear stress developed at the bottom of the boundary layer flow is $2^{0.5}$ higher, this leads to higher bulk

Reynolds number of the flow (see table 1 of chapter 3 of Dutta 2012, also reproduced below). The above is due to the way Re_{τ} is defined using half channel height as the length scale, and the way shear stress is calculated in the DNS code (see below).

$$u_{*,avg} = \sqrt{\frac{\tau_b + \tau_t}{2\rho_f}}$$

Table 3.1: Parameters of DNS simulations for different cases. The table lists shear Reynolds number (Re_τ), shear Richardson number (Ri_τ), particle fall velocity ($\tilde{V}$), $Ri_\tau \tilde{V}$, bulk Richardson number (Ri_b), bulk Reynolds number (Re_b), computational grid resolution ($N_x \times N_y \times N_z$), bottom and top shear velocity ($\tilde{u}_b^*$ and $\tilde{u}_t^*$) and, top and bottom normalized sediment concentration ($\tilde{c}_t$ and $\tilde{c}_b$). Cases with names *caseOx* represent the cases that has slip boundary condition at the top wall, thus representing a boundary layer or an open channel flow. On the contrary, cases with names *caseCx* represent cases that have no-slip boundary condition at the top, as well as the bottom, thus representing channel flows.

Case	Re_τ	Ri_τ	$\tilde{V}$	$Ri_\tau \tilde{V}$	Re_b	Ri_b	$N_x \times N_y \times N_z$	$\tilde{u}_b^*$	$\tilde{u}_t^*$	$\tilde{c}_t$	$\tilde{c}_b$
caseO1	180	1	0.025	0.025	4543	0.012519	96×96×97	1.4144	0	0.71138	1.409
caseC1	180	1	0.025	0.025	2827.6	0.05953	96×96×97	0.99793	1.0022	0.52958	1.8148
caseO2	180	10	0.025	0.25	4720.7	0.014027	96×96×97	1.4141	0	0.6056	1.4497
caseC2	180	10	0.025	0.25	3123.4	0.083042	96×96×97	0.92878	1.0632	0.41199	2.5996
caseO3	180	15	0.025	0.375	4809.2	0.014705	96×96×97	1.4141	0	0.55303	1.4714
caseC3	180	15	0.025	0.375	3598.7	0.16657	96×96×97	0.73146	1.2105	0.28679	6.1347
caseO4	180	18	0.025	0.45	4866.9	0.015309	96×96×97	1.4141	0	0.52313	1.4714
caseC4	180	18	0.025	0.45	3615.2	0.1731	96×96×97	0.73146	1.2105	0.28679	6.3958
caseO5	180	1	0.05	0.05	4564.7	0.026426	96×96×97	1.4128	0	0.49686	1.4128
caseC5	180	1	0.05	0.05	2851	0.13767	96×96×97	0.99441	1.006	0.25769	3.2793
caseO6	180	5	0.05	0.25	4726.2	0.027698	96×96×97	1.4143	0	0.3951	2.0658
caseC6	180	5	0.05	0.25	3226.2	0.24242	96×96×97	0.88154	1.1069	0.16762	6.9809
caseO7	180	1	0.01	0.01	4529.9	0.004932	96×96×97	1.4145	0	0.87402	1.1473
caseC7	180	1	0.01	0.01	2814.1	0.022832	96×96×97	0.9997	1.0004	0.78218	1.2704

So, it is not that self-stratification is less important for boundary layers; the difference one sees between the two flows is mainly because the bulk Reynolds of the flow for the boundary layer cases are higher than the channel flow cases. A flow with higher Reynolds number will require higher level of self-stratification ($\tilde{V}Ri_{\tau}$) to generate the same level of effect on the flow. In the set of Boundary-Layer flow simulations plotted in the manuscript, we never reach the level of self-stratification that it can have a dramatic effect on the flow. If the level of self-stratification is high enough, for the boundary-layer flow we should get similar level of effect when compared with the channel flow.

That apart, even if the two flows had the same bulk Reynolds number; in order to induce the same dramatic response from the flow, boundary layer flow would require higher value of $\tilde{V}Ri_{\tau}$ than the channel flow case. This is evident from the sediment induced stratification studies done on Turbidity currents by Cantero et al. (2009a) and Shringarpure etal. (2012); where the $\tilde{V}$ (at Ri_{τ} ~ 12) required by a channel flow and boundary layer to demonstrate dramatic turbulence suppression is 0.023 Cantero et al. (2009a) and 0.0265 Shringarpure etal. (2012), respectively.

4) The authors may want to consult experimental data and analysis of the sediment diffusivity by Cellino Massimo.

Answer:

The authors would like to thank the reviewer for suggesting the work of Massimo Cellino. We have reviewed Massimo Cellino's papers, and they have provided us some additional insights into the effect of suspended sediment on open-channel flows. The paper Cellino and Graf (1999) talks about sediment laden flows under capacity and non-capacity conditions. Cellino and Graf reported the suppression of turbulence due to presence of suspended sediment. In the study, momentum and sediment diffusion coefficients were found to be smaller than the theoretically predicted value. This observation matches with results published in our current manuscript. They also observed that in the listed experiments, sediment diffusion coefficient was always less than the momentum diffusion coefficient. Cellino and Graf (2000) also studied sediment suspensions in open-channels with bedforms. In general the analysis is similar to their previous study but in this article they had tried to understand the importance of the bed-forms and how they might affect the suspended sediment profile. Finally Graf and Cellino (2002) published an article in which, they summarize major portions of all the experiments performed by Cellino (1998) during his Ph.D research. The article on basis of the experiments emphasizes that in general the ratio of sediment and momentum diffusion coefficient is less than 1.0 but due to presence of bed-forms the value increases to greater than 1.0.

Specific Comments:

1) P926 L19-20 and Figure 1: What is the accuracy in the estimation of Kz/Hu*? The uncertainty in shear velocity estimations is known to be rather large, and the important near-bed gradients in concentration may also generate considerable uncertainty.

   Answer:

   Kz/Hu* plotted in Figure 1 was estimated by Coleman (1970) using sediment concentration profiles measured by Anderson (1942) at the Enoree river. The plot reflects the estimation of Kz/Hu^* by Coleman (1970) using suspended sediment concentration data from experiments he conducted in the lab [please see figure below]. As with any experiment or field measurement, there is always an inherent error/uncertainty around the measurement. But if good measurement practices are followed, like repeating measurements and then ensemble averaging them to get the final result etc., then the inherent error can be reduced considerably. The measurement technique discussed by Coleman (1970) and Anderson (1941, 1942) is pretty robust, so we think we can be certain about the data. Also, u^* is not measured directly but is back-calculated from the measured time-averaged velocity profiles using the velocity defect law. Again, some error may creep in due to inherent assumptions of the velocity defect law, but for the purpose of the present study it should be fine.

If one observes the plot below based on Coleman's own lab experiments, when compared it with Figure 1 in the manuscript, the apparent trends of Kz/Hu* for both the cases is obvious. So, we think we can be fairly certain about estimated Kz/Hu* in Figure 1 of the manuscript. Additionally, we have actual experimental records of Coleman (1986) and they were used to estimate Kz/Hu* plotted in Figure 8 of the manuscript. The values of Kz/Hu* in Figure 8 are in the same ball park of Kz/Hu* estimated by Coleman (1970). So we think that even though the question of accuracy of estimated Kz/Hu* is important, the values presented in Figure 1 (and the figure below) are robust. In order to make the point about robustness of the plotted data clearer, we have added a section in the manuscript briefly explaining the method used by Anderson (1941) for measuring suspended sediment at Enoree River. At the end of the day, others had published all this work so we have no control over the results obtained by other researches.

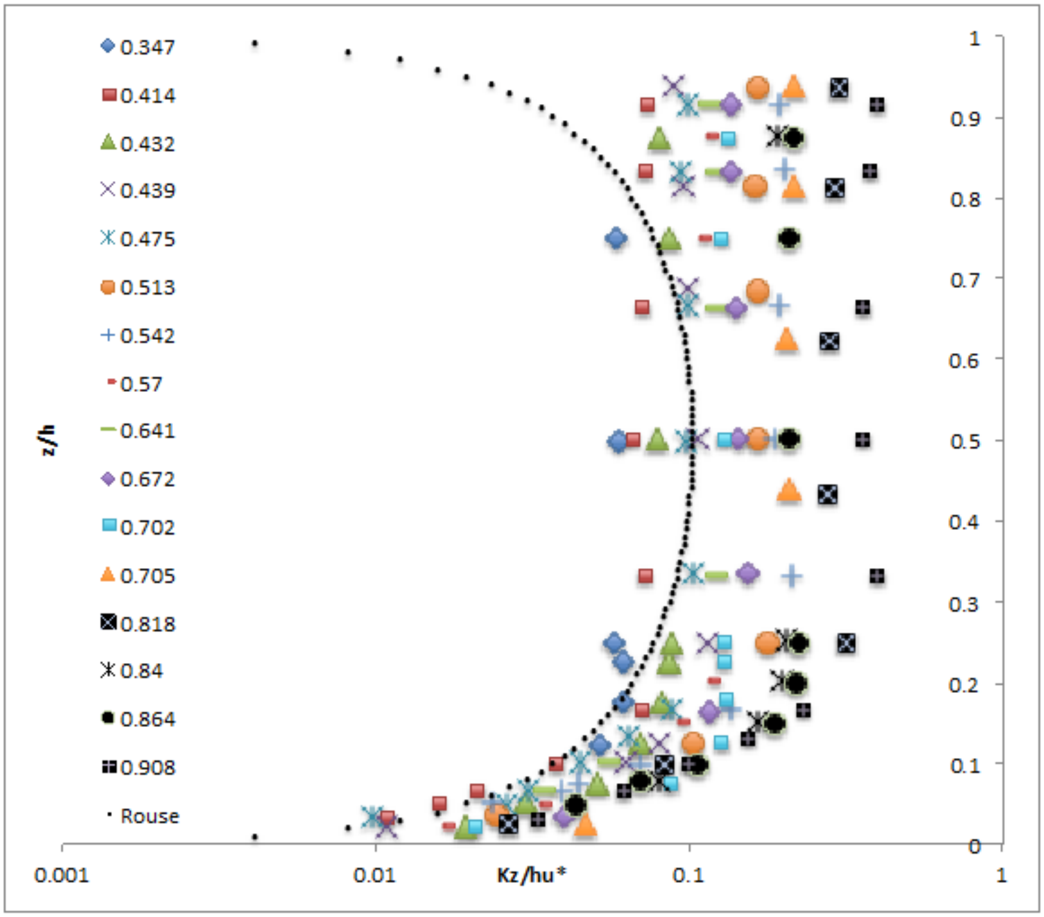

Figure 2: Vertical sediment diffusivity profiles for sediments with different. The data has been reproduced from calculations done by Coleman (1970) on experiments done by him.

2) P927 L8: The sentence “this issue stems from the breakdown of Prandtl’s analogy, due to the inertial effects….” is somewhat confusing. The result in this paper are obtained by neglecting inertial effects (P928 L12), and suggest that stratification effects are the main reason for the deviations between the Rousean profile and experimental data. The statement in the text may be redrafted.

   Answer:

   We agree with the reviewer that we should have been clearer, so thank you for pointing it out. We have changed the manuscript accordingly. The main theme of the paper is to show the effect sediment induced stratification has on vertical sediment diffusivity, through DNS results. Additionally we also show through previous experimental and field data that the trends seen in the DNS results are also reflected in lab and field experiments. In the DNS simulations we have ignored the inertial effect of the sediment, as we wanted to only see the effect of self-stratification. But we nowhere categorically claim that stratification effects to be the “only” reason behind deviations from the Rousean profile. We understand that in nature things are slightly more complex and depending on the size of the particle in suspension we can also have cases where the inertial effect is important and dominant see Nino and Garcia 1998).

3) P929, equation (6): It may be useful to explain why diffusive terms appear in a DNS

   Answer:

   The diffusion term in the sediment transport equation serves multiple purposes. Even though the sediment particles are assumed to be big enough that their Brownian motion can be ignored; it is well established that relatively large particles can also diffuse due to long-range hydrodynamic interactions (Mucha and Brenner 2003 JFM). So the diffusive term takes into account the above mechanism. That apart it also provides a way to re-suspend sediment from the bed (Garcia and Parker 1993). Finally, the diffusion term also provides numerical stability (Cantero et al. 2009a) to the simulations. The above points have been included in the manuscript.

4) P931: It would be useful to provide the grid size in terms of wall units.

Answer:

The grid size is uniform in the longitudinal and transverse direction, and in terms of wall units they are 23.562 and 7.854 respectively. For the vertical a Chebyshev expansion with Gauss–Lobatto quadrature points has been used. This allows very high resolution near the boundaries (walls) and relatively lesser resolution at the center of the domain. In terms of wall units, the resolution near the walls is 0.0964 and the resolution at the center of the domain is 5.889. We would also like to point out that non-linear terms of the Navier-Stokes equation were computed for a grid 1.5 times (only in the horizontal directions) the mentioned grid resolution. It was done in order to get rid of aliasing errors. We have included the information in the manuscript.

5) P934 L25: This sentence is confusing. The DNS results for the channel case show an increase in velocity over the entire water column, which is different from the observed behavior shown in Figure 7.

Answer:

We would like to point out that in Figure 2 and 3 (DNS results), even though the mean velocity of the flow increases, if observed carefully the velocity between z/h -1.0 and -0.8 decreases slightly and is lower than the cases with no (or lower) stratification. The above trend is also reflected by the plotted experimental results in Figure 7, where the velocity between z/h of -0.4 and -1.0 is also decreases. Thank you for pointing out the confusing part. We have made necessary changes in the manuscript to make the above point clearer.

6) P935-936 – Figure 8: Are the differences between the different profiles larger than the uncertainty in the estimation of the diffusivity from the experimental data ? And does the interpretation on P936 accounts for this experimental uncertainty ?

Answer:

Uncertainty in estimation of sediment diffusivity is associated with calculation of u^* and correct measurement of the sediment concentration profiles. One source of error is size of the sediment in suspension. Ideally one would like to have all the sediment particles to be of the same size but they usually come with a certain particle size distribution. This leads to discrepancy between variation of sediment size between experiments, and this has been documented in table 3 of the manuscript. Sediment particle size has been shown to have an effect on level of self-stratification; so variance in the sediment particle size is bound to have an effect on the flow, which might end up slightly obscuring the expected trend of decrease of sediment diffusivity with increase in suspended sediment concentration. We discuss about this in the present version of the manuscript, and we will make it clearer in the revised manuscript. The calculated value of u* in each of the experiment fall within 2.5 % of each other, and this variation was found not to cause any substantial change to the estimated value of Kz/hu*. Multiple sediment diffusivity profiles were plotted in Figure 8, for increasing suspended sediment concentration (Ri_τ). The cases which have similar Ri_τ values (for example case 1 and or 4 and 5), the difference between the Kz/hu* profiles may fall within the uncertainty estimation of Kz/hu*. But if we take cases where the sediment concentration values are quite different (like case 1 and 10), then the expected trend is more obvious. Also, the difference between the Kz/hu* profiles are larger than the expected uncertainty in estimation of Kz/hu*.

7) P936 L20 and Figure 1: It is a strange choice to introduce the topic by means of Figure 1, which shows a trend that is opposite (increase of diffusivity with V) to the subsequent results of the paper.

   Answer:

   The purpose of Figure 1 is to show that vertical sediment diffusivity values do not conform to the generic Rouse profile. Also, even though the general trend is that sediment diffusivity increases with increase in $\tilde{V}$, if observed carefully the trend is not so obvious between certain values of $\tilde{V}$; for example 0.179 and 0.538, 0.209 and 0.101 etc. We think this is due to the fact that in nature there are several mechanisms at work at the same time, inertial effects, self-stratification etc. Niño and Garcia (1998) (see Figure 1 in the paper) pointed out that depending on size of the particle in suspension; it can either damp or increase turbulent energy in the flow; which will consequently either increase or decrease sediment diffusivity. Through laboratory experiments Cellino and Graf (1999) concluded that for their set of experiments, sediment diffusivity was lower than the theoretical value. Again if you see the results published by Coleman (1970) based on his own laboratory experiments (the graph has been reproduced above as Figure 2), there are several cases for which sediment diffusivity is lower than the theoretical value proposed by Rouse.

   In the current study we have tried to quantify the effect suspended sediment induced stratification might be having on sediment diffusivity. Cantero et al. (2009b) showed the importance of stratification on channel flows, and the current study tries to expand that analysis. We thank the reviewer for pointing out the discrepancy between the objective of the study and the general motivation. We have made necessary changes in the manuscript to get rid of the confusion.

Technical Corrections:

P924 L12: replace “were” by “are”: present tense is used elsewhere in the abstract
P927 L9: drop “was”
P927 L15: drop “of sediment”

We thank the reviewer for pointing out the above errors in the manuscript. We have made the necessary changes in the manuscript.

Reference:

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